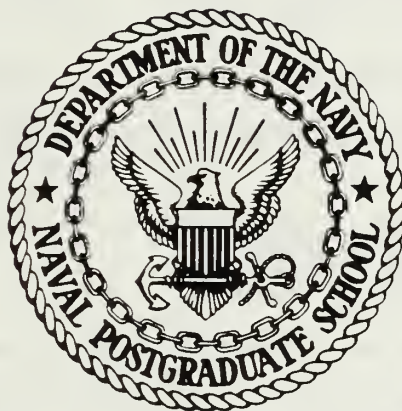


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THESIS

A RADAR MODEL FOR THE INTERACTIVE
SIMULATION OF ENGAGEMENTS AT SEA (ISEAS)

by

Claudio Montero Arizaleta

December 1986

Thesis Advisor:

Robert E. Ball

Approved for public release; distribution is unlimited

T232213

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b RESTRICTIVE MARKINGS	
2a SECURITY CLASSIFICATION AUTHORITY			3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited	
2b DECLASSIFICATION/DOWNGRADING SCHEDULE				
4 PERFORMING ORGANIZATION REPORT NUMBER(S)			5 MONITORING ORGANIZATION REPORT NUMBER(S)	
6a NAME OF PERFORMING ORGANIZATION Naval Postgraduate School		6b OFFICE SYMBOL (If applicable) 67	7a NAME OF MONITORING ORGANIZATION Naval Postgraduate School	
6c ADDRESS (City, State, and ZIP Code) Monterey, California 93943-5000			7b ADDRESS (City, State, and ZIP Code) Monterey, California 93943-5000	
8a NAME OF FUNDING/SPONSORING ORGANIZATION		8b OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c ADDRESS (City, State, and ZIP Code)			10 SOURCE OF FUNDING NUMBERS	
			PROGRAM ELEMENT NO	PROJECT NO
			TASK NO	WORK UNIT ACCESSION NO
11 TITLE (Include Security Classification) A RADAR MODEL FOR THE INTERACTIVE SIMULATION OF ENGAGEMENTS AT SEA (ISEAS)				
12 PERSONAL AUTHOR(S) Montero, Claudio A.				
13a TYPE OF REPORT Master's Thesis	13b TIME COVERED FROM TO	14 DATE OF REPORT (Year Month Day) 1986 December	15 PAGE COUNT 78	
16 SUPPLEMENTARY NOTATION				
17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUB-GROUP	PC-based Computer Simulation of the Air Defense (ISEAS)	
19 ABSTRACT (Continue on reverse if necessary and identify by block number)				
The Interactive Simulation of Engagements At Sea (ISEAS) is a PC-based computer simulation of the air defense of a ship under development at the Naval Postgraduate School. This thesis describes the search radar computer model and the tracking radar computer model, used in ISEAS. These programs are written in the C-language.				
20 DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS			21 ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED	
22a NAME OF RESPONSIBLE INDIVIDUAL Robert E. Ball			22b TELEPHONE (Include Area Code) (408) 6462885	22c OFFICE SYMBOL 67Bp

Approved for public release; distribution is unlimited.

A Radar Model for the Interactive
Simulation of Engagements at Sea (ISEAS)

by

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING SCIENCE

from the

NAVAL POSTGRADUATE SCHOOL
December 1986

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The Interactive Simulation of Engagements At Sea (ISEAS) is a PC-based computer simulation of the air defense of a ship under development at the Naval Postgraduate School. This thesis describes the search radar computer model and the tracking radar computer model, used in ISEAS. These programs are written in the C-Language.

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ACKNOWLEDGMENTS

The advice and assistance provide by Mr. Robert E. Ball in the preparation of this thesis were welcome and helpful. Thanks also to my partners LCDR Dennis Antonio and LTJG Jawad Mamou, who worked with me on this project called ISEAS. I am grateful for their counsel and willing help. Special thanks to Miss Julie Grundman for her excellent grammatical and analytical support during the development of this thesis. Finally I dedicate my work to my family and friends in Venezuela.

I. INTRODUCTION

Military officers, unlike other professionals, cannot practice their profession except in time of war. Consequently, throughout much of history the military has developed, or has sponsored and supported the development of methods and techniques that will permit it to practice its profession in time of peace. One such technique is based on the computer simulation of war and is known as "war gaming".

War gaming is a technique which may be used by a force commander to evaluate the relative merits of various courses of action available to him or her for the accomplishment of his or her mission. In training situations, war gaming allows the commanders and future commanders to exercise and develop their analytical skills, to examine the validity of established doctrine, and to explore the viability of evolving tactical concepts. The general purpose of a war game is an "educational" (decision making experience) or an "analytical" (information evaluation experience) type of game.

The Interactive Simulation of Engagements At Sea (ISEAS) is a PC-based naval war game under development at the Naval Postgraduate School. This game permits the evaluation of various tactical and engineering options under the constraints of a specified set of rules (Figure 1.1). As a naval tactical war game, ISEAS must provide a realistic simulation of detection, engagement, Combat Information Center (CIC), and destruction of the threat.

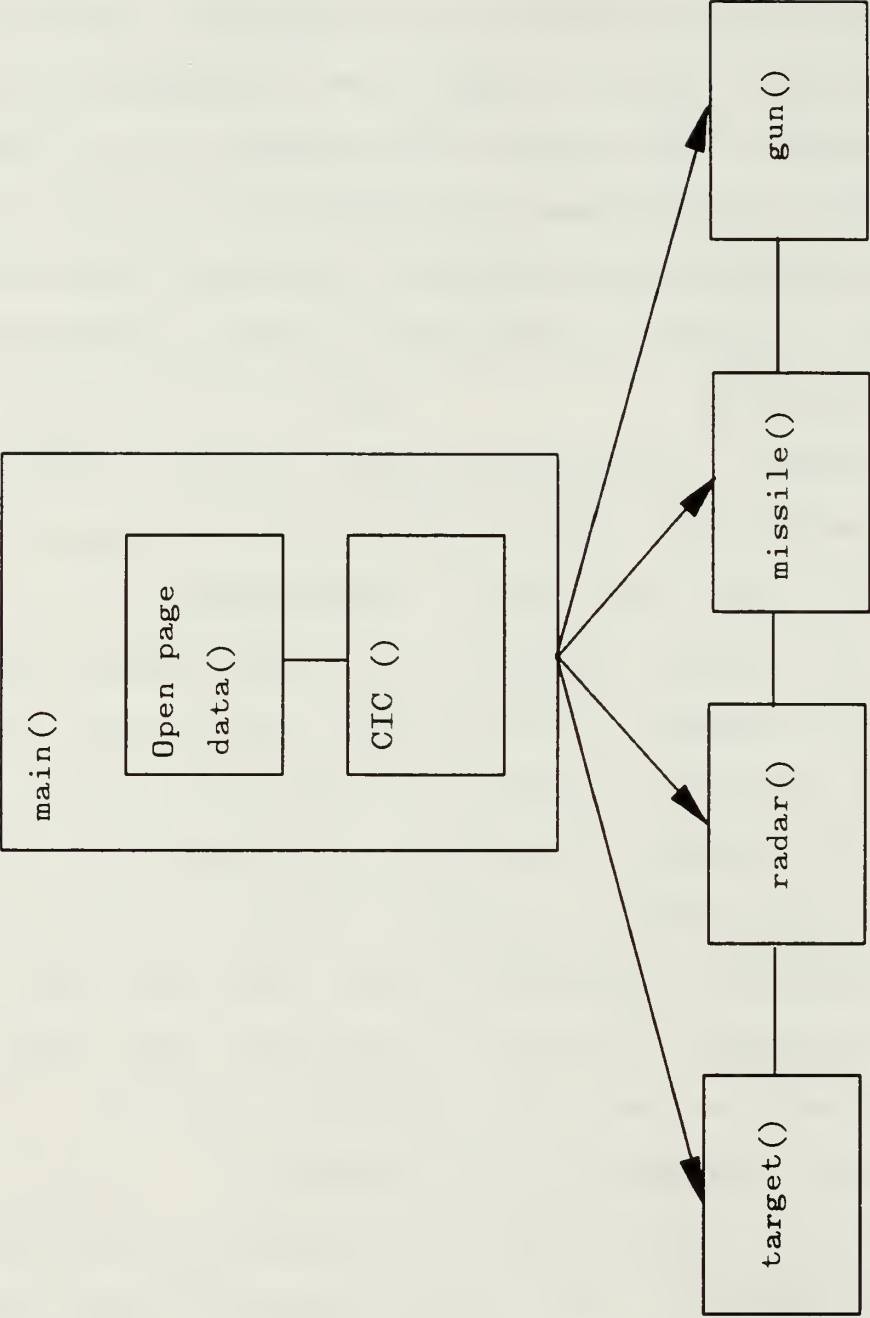


Figure 1.1 ISEAS

The purposes of ISEAS are to give the players experience in supervising an air attack and in examining the effects of engineering changes to the air defense system. Because it can be played over and over again, the war game makes it possible to do what cannot be done in the field, that is, to vary characteristics and to extend the scope and values of limited peacetime experiments.

To be of value, ISEAS must provide a realistic radar detection model for the airborne threat. This thesis describes the development of such a detection model. If the detection of a target cannot be satisfactorily modeled, then its engagement and destruction cannot be simulated, since in the sequence of events it is necessary to detect a target before a weapon system can be brought to bear.

II. SYSTEM DESCRIPTION

This report contains a description of the computer model of a ship-borne air defense radar system. The model is written in C-language for use on a PC microcomputer. A general description of the model is presented in Figure 2.1 and is followed by a detailed documentation.

The function of a modern air defense radar system is to detect, track, select, designate, and direct missiles and guns to an intercept with unfriendly aircraft or missiles. Such a system consists of five main subsystems:

- Search radar(s)
- Tracking radar(s)
- Data processor(s)
- Guided missile interceptors
- Command and control network(s)

The search radar obtains the initial information about approaching air targets. This information is analyzed in the data processor, which selects specific targets for tracking and designates the tracking radars. The tracking radar then provides the data processor with extremely accurate data indicating the target's location and speed. From this information, the data processor chooses an intercept point for the missile trajectory or projectile to engage each target. Guided missiles are then launched by the launching equipment and are guided to the target, possibly by the radar

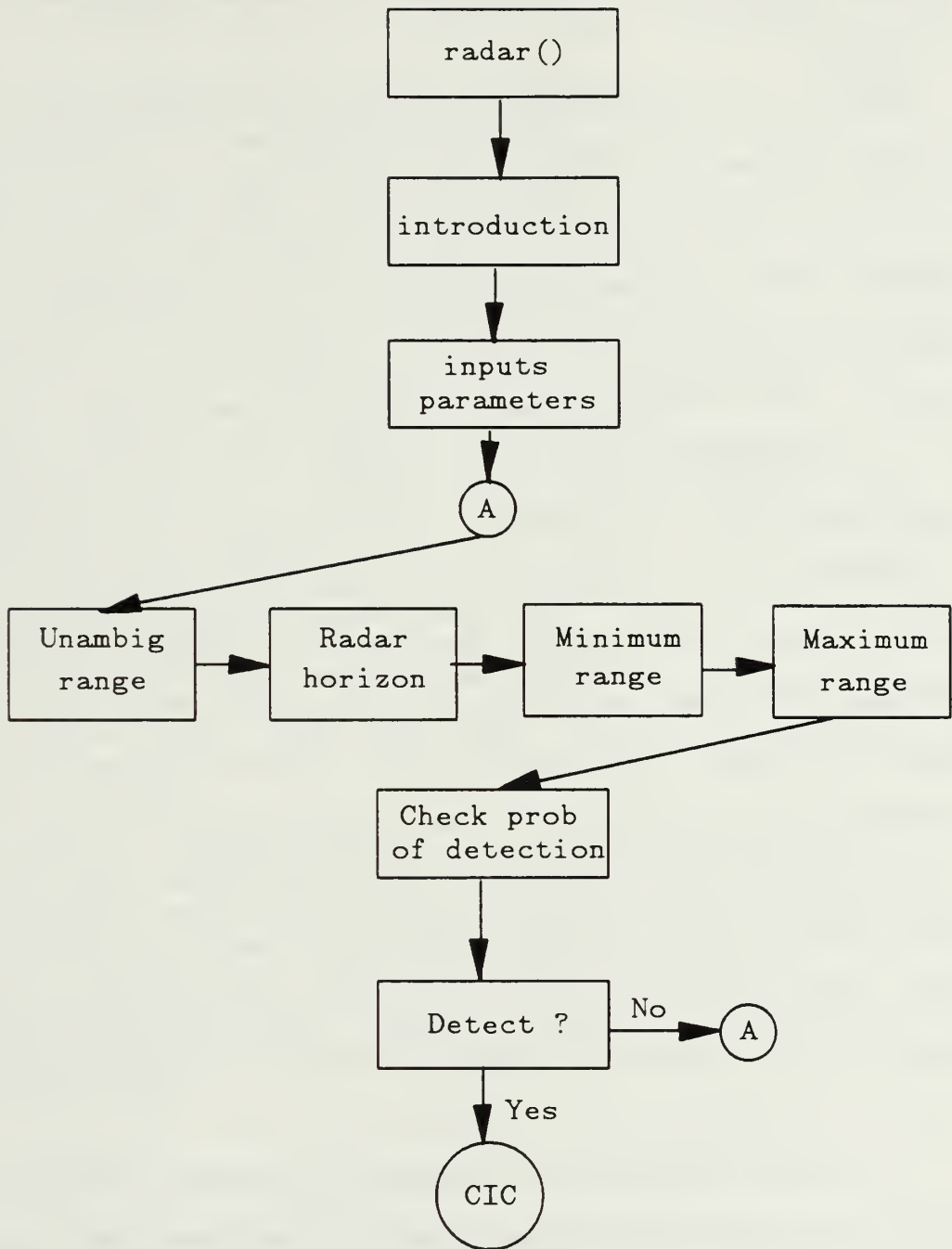


Figure 2.1 Radar Detection

trackers and the data processor. The function of the command and control subsystem is to interconnect the various subsystems.

A. RADAR

Radar is an electromagnetic system for the detection and location of objects. It operates by transmitting a particular type of waveform, such as a single pulse. An elementary form of radar consists of a transmitting antenna emitting electromagnetic radiation generated by an oscillator of some sort, a receiving antenna, and an energy-detecting device or receiver. A portion of the transmitted signal is intercepted by a reflecting object (the target) and is reradiated in all directions. It is the energy reradiated in the direction of the receiving antenna that is of prime interest to the radar. The receiving antenna collects the returned energy and delivers it to a receiver, where it is processed to detect the presence of the target and to extract its location and possibly its relative radial velocity. The distance to the target for a monostatic radar is determined by measuring the time taken for the radar signal to travel to the target and back. Radio waves travel at 328 yds every microsecond, i.e every millionth of a second, which means that every microsecond represents 164 yds of range.

The echo returned to the radar by a simple, point-source target will be an exact reproduction of the transmitted signal, shifted in time by an amount corresponding to the range delay and shifted in frequency by the "Doppler shift" due to the target relative radial velocity. [Ref. 1]

If "n" echo pulses, all of the same signal-to-noise ratio, were integrated (the process of summing all of the radar echo pulses for the purpose of improving detection) by an ideal predetection integrator, the resultant signal-to-noise (power) ratio would be exactly n times that of a single pulse. If the same n pulses were integrated by an ideal postdetection device, the resultant signal-to-noise ratio would be less than n times that of a single pulse. This loss in integration efficiency is caused by the nonlinear action of the second detector. Experimental measurements of the operator's ability to detect signals on an A-scope showed the integration-improvement factor to be root (n), or 1.5 dB per doubling of the number of pulses integrated.

Since the range to the target can be predicted with reasonable confidence, these ranges have been viewed as being deterministic in character.

Two basic characteristics of a target can be obtained from its radar echo; metric characteristics and signature characteristics. Metric characteristics give the target location in terms of range and angular measurements. Signature characteristics give the target size and shape.

B. PULSE MODULATED SEARCH RADAR

A pulse modulated air search radar is an active system which emits spaced pulses of electromagnetic energy. These pulses of energy illuminate an airborne target and are reradiated by it. A portion of the reflected energy is received by the radar set, and the range to the target is determined by the time differential

between the transmission of a pulse and the receipt at the radar receiver of the target echo.

The range to the target from the radar is determined by the following relation:

$$R = C\_SPEED * t / 2 \quad (1)$$

where

R = Range to the target

t = Time difference between the transmission of a radar pulse and the receipt of the target echo

C_SPEED = The Speed of Light

C. TRACKING RADAR

A tracking radar is one whose function is to report the position of a moving target and to follow its movement in both range and angle. The function of these radars is not the detection of a target. Their range performance is considered in a different sense from that of a surveillance or search radar. Typically, a tracking radar acquires new targets on the basis of approximate target position information furnished to it by a search radar. The range-angle gates of the tracking radar are positioned at the range and angle specified by the search radar. In some cases the tracking radar is scanned in both range and angle over a limited volume of space surrounding the designated position. If the echo from the target appears within the gate with an adequate signal-to-noise ratio, the tracking radar "locks on" to the target echo. Therefore, the problem of analyzing the range performance of a tracking radar is reduced to that of finding the range at which

the signal-to-noise ratio has the value required for successful target acquisition or lock-on.

D. TIME-STEP AND EVENT-STORE GAMES

Computer games are conducted according to either a time-step or event-store method. In the time-step method all moves are made for a fixed time interval. The computer calculates the positions of the threat at regular time steps. At the end of each step, it examines each interaction that might have occurred, decides if it did occur, and, if it did, determines the outcomes.

In the event-store or critical event method, the computer, instead of advancing the game by constant time increments, jumps ahead to the next event that has a probability of occurring and that is vital to the outcome of the game. No positions, distances, or times are determined until they can be used.

As each new event is generated an "event word" is formed. This word tells when the event will occur, what type of action is to be taken, and what offensive and defensive units are involved. The word is then stored according to its time of occurrence in a chronological list of future events.

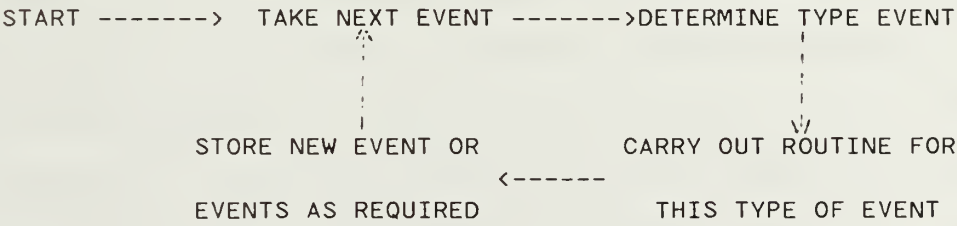


Figure 2.2 Event Store Routine

The sequence of the game is as follows: Input the data and the program into the computer. The machine then calculates and stores in proper order all the events that can be predicted at the start of the game. The program then takes the first event in store, calculates the outcome, stores this, forms words for any required new events, and removes any units that will no longer affect the game results. With further events in store, they are considered in order, until the last event is considered.

One advantage of the event-store method is that target detections, weapon releases, weapon kills, etc, occur in proper time sequence. Another advantage is the ease and flexibility of programming. This is particularly true in the C-language when an effort is made in the original coding to (1) allow space in the computer for expansion, and (2) to make each event a selfcontained routine. Since experience shows that all games need some modification, this feature is well appreciated. One disadvantage of the event-store technique is the large amount of memory that must be set aside for storing future events.

E. DETERMINISTIC MODEL

Computer models, like other game models, may be either deterministic or stochastic in their treatment of chance events. A deterministic model has the property that the result of a modeled event is completely determined by the data which describes the situation. In such a model, the results of probabilistic events are determined by expected values for the events; e.g. if the probability of

aircraft survival over a given route is 0.20, then if ten aircraft fly along this route, the deterministic model says exactly eight are killed and two are alive at the end of the route. A stochastic or Monte Carlo model has the property that the result of a modeled event is determined by the interaction of the model rules with a random process (or processes). For instance, the stochastic model might determine how many of the ten aircraft survive by comparing ten random numbers with the survival probability 0.20; for each of ten numbers randomly drawn between 0.0 and 1.0 less than 0.20 of aircraft survives. Repeated runs of a stochastic model reveal the distribution of possible outcomes, not just an expected outcome. Stochastic models are also called probabilistic models.

III. ENGINEERING DESIGN

The radar computer program presented here was developed to provide the radar performance required in ISEAS. The program computes the performance of ship-based search and fire control radars against targets in the presence of clutter and jamming. The effects of attenuation due to atmosphere and the accuracy of radar measurements are included in the program. The program uses the basic equations for radar performance described by M. I. Skolnik [Ref. 1] and S. A. Hovanessian [Ref. 2].

The development of a computer program requires an understanding of the problem, a knowledge of the instructions which the computer is capable of performing, the language by which it operates, the capacity of the memory, and the method of data representation.

The first step in the preparation of the program is the construction of a generalized model, such as the flow chart on Figure 3.1. Each of the modules presented on the figure are presented below.

A. RADAR HORIZON

A radar signal is an electromagnetic wave that travels in straight lines. This means that a target can only be detected if it is on a line-of-sight from the radar. That is, it will not be visible if it is below the horizon.

The distance from a radar at height h_1 to the horizon (D) may be determined by simple geometry. The radius of the earth is

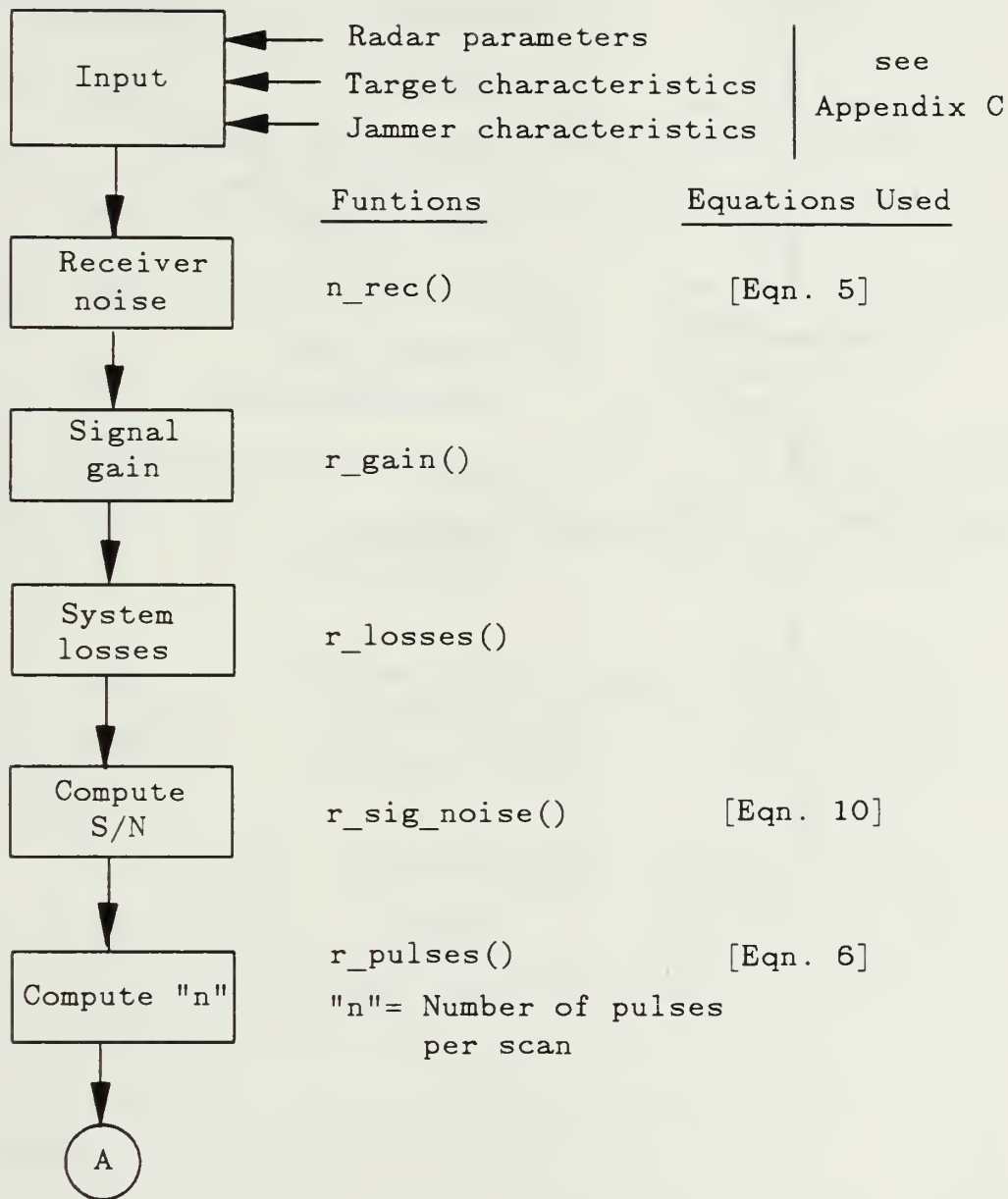


Figure 3.1 Flow diagram radar equation

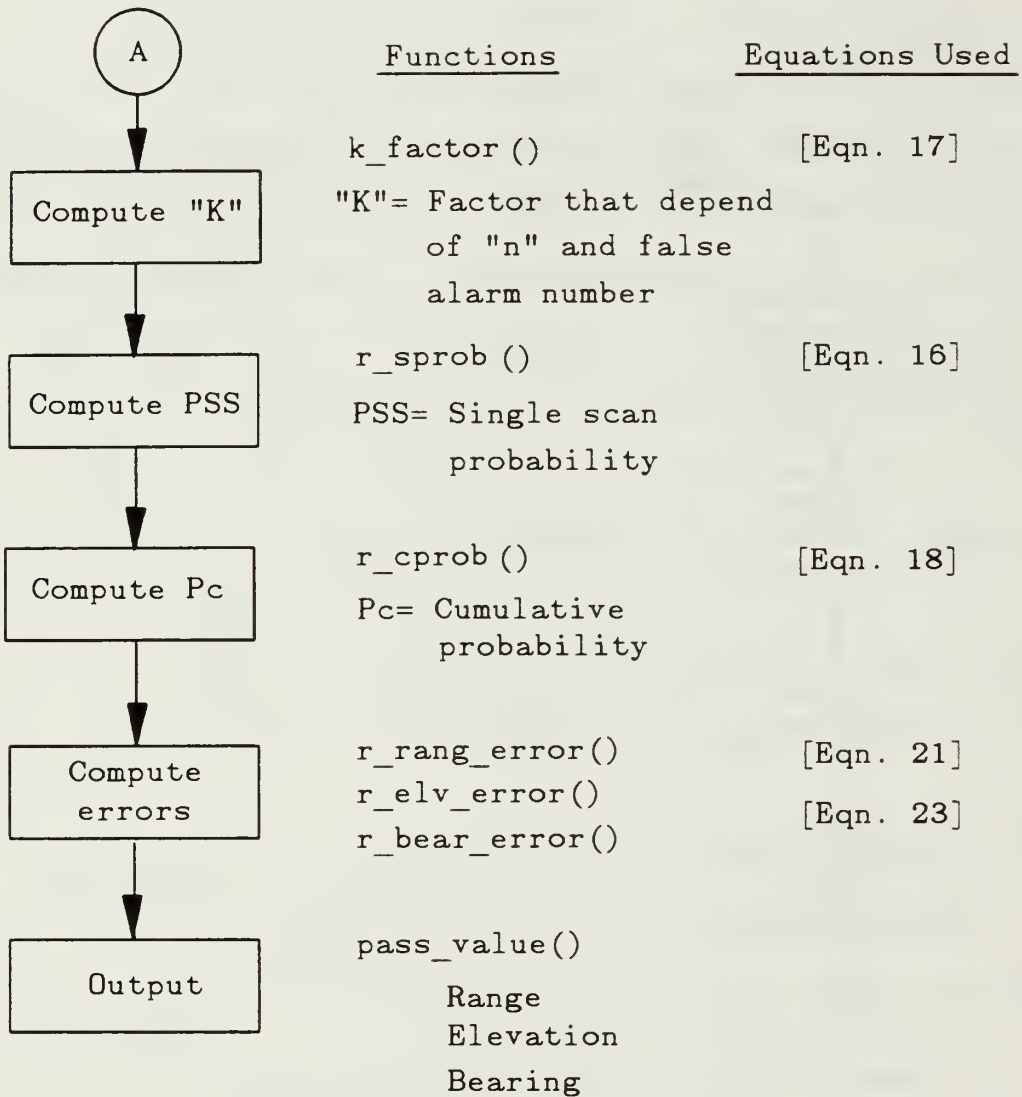


Figure 3.1 Flow diagram range equation (cont)

approximately 3450 N.M. Because the radar direction changes due to refraction of the radar signal by the atmosphere, the radar earth's radius is taken as

$$4/3 * 3450 = 4600 \text{ N.M.}$$

assuming a factor of 4/3 due to refraction.

Thus, the distance to the reference radar horizon is given by [Ref. 3]

$$D = 1.23 \text{ root}(h.1)$$

where D is in nautical miles and h.1 is in feet.

If the target is at a height h.2, in feet, the maximum range from the radar at which it can be detected (R_{horiz}) is given by [Ref. 3]

$$R_{\text{horiz}} = 1.23 * [\text{root}(h.1) + \text{root}(h.2)] \quad (2)$$

For example, if

$$h.1 = 30 \text{ feet}$$

$$h.2 = 400 \text{ feet}$$

$$R_{\text{horiz}} = 1.23 * [5.48 + 20.0] = 33 \text{ N.M.}$$

B. MINIMUM RANGE

When range measurement is made by using a pulsed waveform and by measuring the elapsed time between the transmitted pulse and the received signal, there are limitations to the minimum range that can be measured. The pulse width is one limitation,

since the receiver cannot receive a signal until the transmitter is turned off. Another limitation is the time interval required to turn the receiver on after the transmitter pulse is turned off. The latter is referred to as the recovery time. The minimum range is given as [Ref. 4].

$$R_{\min} = C\_SPEED * (T + RT) / 2.0 \quad (3)$$

Where

T = Pulse width

RT = Recovery time

For example, if

$$T = 3.0 \text{ msec} , \quad RT = 1.0 \text{ msec}$$

Then

$$R_{\min} = 984 \text{ ft / msec} * (3.0 + 1.0) \text{ msec} / 2.0$$

$$R_{\min} = 1968 \text{ ft.}$$

A radar system that must have short range capability must use a very short pulse width with a quick receiver recovery time.

C. MAXIMUM UNAMBIGUOUS RANGE

During one complete transmit-receive cycle, a radar pulse must travel from the radar to the target and return. Echo signals received after an interval exceeding the pulse repetition period are called multiple-time-around echos. They can result in erroneous

or confusing range measurements. That is, the radar "sees" unambiguously only those signals which return to it between successive pulses. Consequently, the maximum unambiguous detection range (R_{unamb}) is determined by the pulse repetition frequency (PRF)

from the equation [Ref.1]

$$R_{unamb} = C\_SPEED / (2.0 * PRF) \quad (4)$$

For example, if

$$PRF = 1000 \text{ pulses /sec}$$

Then

$$R_{unamb} = 164,000 \text{ yds} = 82 \text{ nautical miles.}$$

One method of distinguishing multiple-time-around echos from unambiguous echoes is to operate with a varying PRF. The echo signal from an unambiguous range target will appear at the same place on the A-scope on each sweep regardless of whether the PRF is modulated or not.

D. SYSTEM LOSSES

There are many sources of power loss in the signal and the echo. The overall loss is called the system loss and is the sum of all of the losses. For that reason, if the effect of the system loss is included in the radar range equation, the equation will give a more accurate picture of practical achievable ranges.

The transmitting losses include such items as power transmission efficiency, wave guide and antenna losses, and the duplexer loss. The total of these losses, usually referred to as plumbing loss, in a typical radar may be approximately 1 to 3 decibels. [Ref. 2]

In the receiving loop, the losses will include the antenna, wave guide, RF or parametric amplifier, mixer, and IF amplifier. These losses may be on the order of 1 to 3 decibels.

In addition to the above losses, the electromagnetic signal traveling through the atmosphere suffers another loss which is termed atmospheric attenuation. This loss is caused primarily by absorption of energy by atmospheric gases. For frequencies below 10 GHz, it is between 0 to 3 decibels depending on the transmitting frequency, the antenna elevation angle and the target range.

As the antenna beam sweeps the target, the antenna gain illuminating the target varies. The radar range equation, however, uses the maximum gain of the antenna along the boresight axis as the reference. The gain variation of a scanning antenna as it illuminates the target will give rise to an antenna beam shape loss during the scan. These losses, may be approximately 1 to 3 decibels, and are known as beam shape losses.

E. ATMOSPHERIC ATTENUATION

Attenuation results when a portion of the energy incident on the molecules of the atmosphere is absorbed as heat and is lost. The reduction in radar signal power when propagating over a distance R and back (two-way path) may be expressed as $10^{-(\alpha * R/5)}$ where α is the (one-way) attenuation coefficient measured in units

of distance. At frequencies below about 1 GHz, the effect of atmospheric attenuation is negligible. Above 10 GHz, it becomes increasingly important. The large attenuations experienced at millimeter wavelengths is one of the reasons long range radars are seldom found above 35 GHz.

From Figure 12.10 of Reference 1, the attenuation coefficient for frequencies between 1 GHz and 15 GHz is given as

$$\alpha \text{ (Db / N.M)} = 0.003001 + 0.000393F$$

Where F is $r_{\text{freq}} / \text{GHz}$

F. RECEIVER NOISE

Noise is the important factor that limits the receiver sensitivity. It is unwanted electromagnetic energy which interferes with the ability of the receiver to detect the echo. No matter whether the noise is generated by an internal thermal mechanism (noise generated by the thermal motion of the electrons in the receiver input stage) or by some other mechanism, the total noise at the output of the receiver is the thermal-noise power obtained from an ideal receiver multiplied by a factor called the noise figure that is a function of a type of receiver.

$$\text{Thermal noise} = K * T * B_n$$

where

T = Temperature in degrees Kelvin

K = Boltzmann's constant

B_n = Receiver bandwidth in Hz

And the total receiver noise (n_{rec}) can be written

$$n_{rec} = F * K * T * B_n \quad (5)$$

where F is the Noise figure

For example, if

$$B_n = 5.0 \text{ MHz}$$

$$F = 5.0$$

Then

$$n_{rec} = (5.0) * (1.38 * 10^{-23}) * (290) * (5.0 * 10^6)$$

$$n_{rec} = 1.005 * 10^{-13} \text{ W}$$

G. NUMBER OF PULSES

The number of integrated pulses per scan (n) used in the equation for the probability of detection can be calculated for many regular scan patterns. For a fan beam sweeping in azimuth, n is directly proportional to the antenna beamwidth area (BA) and PRF, and inversely proportional to antenna scan rate. Thus, according to Reference 5

$$n = \frac{ST * PRF * BA}{SFOV} \quad (6)$$

Where

ST = Scan time = $360 / AZR$, sec

AZR = Antenna azimuth scan rate, deg / sec

PRF = Pulse repetition frequency, pulses / sec

BA = Beam area = $(BAZ) * (BEL)$, square degrees

BAZ = Antenna azimuth beam width, deg

BEL = Antenna elevation beam width, deg

SFOV = Search field-of-view, square degrees
= $360 \times (\text{BEL})$

For example, if

AZR = 60 deg/sec

PRF = 240 pulses/sec

BAZ = 2.5 deg.

BEL = 20 deg.

Then

ST = $360 / 60 = 6$ sec

BA = $(2.5) \times (20) = 50$ square deg.

SFOV = $(360) \times (20) = 7200$ square deg.

And

$$n = \frac{(6) \times (240) \times (50)}{7200} = 10 \text{ pulses / scan}$$

H. MAXIMUM DETECTION RANGE

The maximum detection range is a useful starting point in determining the maximum range at which an airborne target can be detected. The maximum detection range (R_{max}) can be given in the form [Ref. 1]

$$R_{\max} = \frac{P_t^2 \cdot G_r^2 \cdot \lambda^2 \cdot \text{RCS}}{(4 \cdot \pi)^3 \cdot P_m} \quad (7)$$

Where

- $R_{\max}$ = Maximum detection range, meters
- P_t = Transmitted power, Watts
- G_r = Antenna gain, non-dimensional
- λ = Wavelength, meters
- RCS = Target radar cross section, sq. meters
- P_m = Minimum power required at the receiver for detection at some desired probability of false alarm.

For example, if

- $P_t = 1. \text{e}6$ watts
- $G_r = 1000 = 30 \text{ db}$
- $\lambda = 1.0$ meter
- $P_m = 5. \text{e}-13$ watts
- RCS = 1.0 Sq.meter

Then

$$R_{\max} = 178,000 \text{ meters} = 90 \text{ Nautical miles}$$

The value of P_m is usually determined in relation to the radar receiver noise in the form [Ref. 5]

$$P_m = \frac{(S/N) \cdot N_r}{c} \quad (8)$$

Where

$(S/N)_c$ = Signal to noise ratio to give the required probability of false alarm

N_r = Receiver noise, Watts

I. ELECTRONIC COUNTER-COUNTERMEASURES

All radars, civilian and military, must be able to operate in the crowded electromagnetic environment that results from the transmissions of other radiating sources, both in the radar's own band as well as from other bands. Military radars, however, must also operate in a hostile environment where they may be subjected to deliberate interference designed to degrade their performance. The various methods for interfering electronically with radar are called electronic countermeasures, or ECM. Active ECM is sometimes referred to as jamming. There is also passive ECM, such as chaff, which reflects radar energy to create clutter or a false target. The methods employed to combat ECM are called electronic counter countermeasures, or ECCM.

As a general rule, good radar design can reduce vulnerability to electronic countermeasures. Good design is based on maximizing the ratio of the signal energy to noise power per hertz (E/N_0), as well as employing techniques to reduce mutual interference. A radar should be designed more conservatively, with large power and large antenna aperture, than the minimum required for marginal detection.

1. Noise Jamming

Internal receiver noise generally limits the sensitivity of most microwave radars. Raising the noise level by external means, as with a jammer, further degrades the sensitivity of the radar. A sensitive receiver with a low noise figure may be desirable in many civilian applications of radar, but in military applications it is not always an asset since it makes the receiver more vulnerable to jamming.

Noise jamming, which is one of the most effective ECM techniques, involves generation of noise signals which are spread over the frequency bandwidth of the receiving radar. Noise jamming, in effect, increases the noise level of the receiving radar, reducing, and in many cases eliminating, its capacity to detect and/or obtain information on targets. Locating the jammer might not be as important as locating the attacking missiles or aircraft screened by the jammer, especially when the jamming aircraft is beyond the range of defensive weapons. A jammer that operates outside the range of normal defenses is known as a stand-off jammer. An important ECCM tactic is to engage hostile jammers with home-on-jam (HOJ) missile guidance. If the jammer is radiating, HOJ is generally a better guidance technique than is radar guidance.

The jammer power received at the radar varies inversely as the square of the distance between radar and jammer (one-way propagation), while the radar echo power varies with distance inversely as the fourth power (two-way propagation). There will be some

distance at which the radar echo will burn through the jammer signal. This is also called the self-screening range, or the cross-over range.

2. Single Scan Probability

For a jammer that is emitting a power of P_j watts per hertz in the frequency band of the radar receiver, the jamming signal N_j seen by the radar receiver is [Ref. 5]

$$N_j = \frac{P_j * Br * G_j * Gr * \text{Lamd}^2}{(4 * \pi)^2 * R_j^2} \quad (9)$$

where

P_j = Jammer power, watts per hertz

Br = Radar receiver bandwidth, hertz

G_j = Jammer gain (antenna focusing)

Gr = Radar antenna gain

Lamd = Wavelength, meters

R_j = Range from jammer to radar, meters

If the assumption is made that the jammer signal N_j is additive with the receiver noise N_r , then the signal to noise ratio in the receiver is

$$S/N = \frac{S}{N_r + N_j} = \frac{\frac{P_t \cdot G_r^2 \cdot \lambda^2 \cdot RCS}{(4\pi)^3 \cdot R_t^4}}{N_r + \frac{P_j \cdot G_j^2 \cdot G_r \cdot \lambda^2 \cdot B_r}{(4\pi)^2 \cdot R_j^2}} \quad (10)$$

where

R_t = Range from target to radar in meters.

Defining the reference target range (R_o), and the reference jamming range (R_k) as

$$R_o^4 = \frac{P_t \cdot G_r^2 \cdot \lambda^2 \cdot RCS}{(4\pi)^3 \cdot N_r} \quad (11)$$

$$R_k^2 = \frac{P_j \cdot G_j^2 \cdot G_r \cdot \lambda^2 \cdot B_r}{(4\pi)^2 \cdot N_r} \quad (12)$$

The characteristics of a given radar system against a target of specified radar cross section can be specified by the value of R_o , which is the range for a signal to noise ratio of unity, or a S/N of zero decibels.

Then

$$S/N = \frac{(R_o / R_t)^4}{1 + (R_k / R_j)^2} \quad (13)$$

J. PROBABILITY OF DETECTION

The probability of target detection depends on the value of the signal-to-noise ratio (with or without jamming) and the threshold setting in the detection circuitry. Higher values of S/N signify higher values of target return power for a given noise power. Higher S/N thresholds for detection raise the level of echo power at which target returns will be detected, thereby degrading detection capability. But, on the other hand, higher thresholds reduce the rate of false alarms (noise crossing the threshold level) making the detection of targets more reliable.

Expressions relating the single scan probability of detection (PSS), as a function of the signal-to-noise ratio with the false alarm probability, as a parameter are given below. The false alarm probability P_n refers to the condition where the noise exceeds the threshold setting resulting in a false detection.

With this information, the designer of a radar system can determine the probability of detecting a given target as a function of the reference target range (R_0).

The S/N at any range R can be calculated using the equation

$$S/N = (R_0/R)^4 \quad (14)$$

and the single scan probability of detection at range R is given by [Ref. 5]

$$PSS = \exp [-K / (S/N)] \quad (15)$$

$$PSS = \exp [-K * (R/R_o)^4] \quad (16)$$

where

R = Range to target

K = A factor for each radar which is a function
of n and m

n = No. of pulses per look (scan)

m = False alarm number

The K-factor can be calculated as follows [Ref. 5]

If $1.e-6 \leq m \leq 1.e-12$

$$\begin{aligned} K_{db} &= 10 \log K \\ K_{db} &= -6 \log n + .4 \log m + 7.2 \\ K &= 10^{.1(K_{db})} \end{aligned} \quad (17)$$

For example, if

For $n = 10$, $m = 10e-12$, $R = R_o$

$K_{db} = -6 + 4.8 + 7.2 = 6$

$K = 4.$

Thus, the single scan probability of detection becomes

$$PSS = \exp [-4. (1)^4] = .018$$

and for $(R / R_o) = 1 / 2$

$$PSS = .78$$

For $n = 10$, $R = R_o$ and various false alarm numbers

log m	=	2	4	6	8	10	12
PSS	=	.36	.22	.105	.068	.036	.018

Given the probability of detection in a single scan of the target, the cumulative probability of detection over several scans can be calculated. In scanning radars, targets are illuminated every scan or radar frame. For the "s" th scan of the target, there will be a certain probability of detection ($\bar{P}_d^s$) based on the target range and radar cross section, both of which can vary with each scan. Thus, $\bar{P}_d^s$ is generally a function of time. The cumulative probability of detection is obtained by "adding" the probability of detection at each scan. The term "adding" is used in a probability sense rather than an algebraic sense. The probability that the target has been detected after "s" scans, is given by

$$\bar{P}_d^s = 1 - (1 - PSS)^1 * (1 - PSS)^2 \dots (1 - PSS)^s$$

If PSS is essentially a constant value for each scan, then, $\bar{P}_d^s$ can be simplified as [Ref. 6]

$$\bar{P}_d^s = 1 - (1 - PSS)^s \quad (18)$$

R refers to the range at which a 90% cumulative probability of detection is achieved.

The cumulative probability has sometimes been proposed as a measure of the detectability of a radar rather than the single scan probability of detection. In practice, the use of the cumulative probability is not easy to apply. Radar operators do not usually use such a criterion for reporting detections. They seldom report a detection the first time it is observed, as is implied in the definition of cumulative probability. Instead, the criterion for reporting a detection might be a threshold crossing on two successive scans, or a threshold crossing two out of three scans, etc. In track-while scan radars, the measure of performance might be the probability of initiating a target track rather than a criterion based on detection alone.

K. CW RADAR

A CW radar to measure both range and velocity of a single target is accomplished by broadening the transmitted frequency spectrum by frequency modulating the carrier frequency. Range, in terms of time, can be determined by measuring the difference between the received and transmitted frequencies.

CW radars are used also for CW missile guidance systems and for measuring velocity. For the latter, The transmitter generates a continuous (unmodulated) oscillation of frequency (f_0), which is radiated by the antenna. If the target is in motion with a velocity V_r relative to the radar, the received signal will be shifted in

frequency from the transmitted frequency f_0 by an amount $\pm f_d$ given by [Ref. 1]

$$f_d = \frac{2 * V_r}{\lambda_{md}}$$

The received echo signal at a frequency $f_0 \pm f_d$ enters the radar via the antenna and is heterodyned in the detector (mixer) with a portion of the transmitter signal f_0 to produce a doppler frequency shift, f_d , that gives the relative velocity of the target.

CW radars are smaller than corresponding pulse radars, although two antennas are required, and can operate against a target to almost zero range. As in surveillance radars, tracking radars are also limited by coverage volumes and target cross sections. The same considerations apply as in the case of search radars. The target must be within the coverage limits and within those limits

$$R = R_0 [RCS]^{0.25} \quad (19)$$

where

$R_0 = R$ for RCS equal to 1.0 square meter

But for tracking radars we will operate with relatively narrow beamwidths at mid-frequencies (2000 to 6000 MHz).

L. ACCURACY OF RADAR MEASUREMENTS

The parameters of interest in radar applications are the range (time delay) and the angle of arrival. Therefore, the theoretical accuracies of radar measurements are given below.

1. Range Accuracy

The measurement of range is the measurement of time delay

$$Tr = 2 * R / C\_SPEED$$

In terms of the effective bandwidth, the time-delay error (&Tr) becomes [Ref. 1]

$$\&Tr = \frac{1}{\text{betha} * (2 * S/N)^{0.5}} \quad (20)$$

where betha, the effective bandwidth, is

$$\text{betha} = \frac{2 * Bn}{T}$$

and the range error (&R) will be given as

$$\&R = (C\_SPEED / 2) * \&Tr \quad (21)$$

The rms time-delay error of a waveform with a uniform frequency spectrum of width B is given as [Ref. 1]

$$\&Tr = \frac{1.732}{\text{PI} * B * (2 * S/N)^{0.5}} * \frac{\sin x}{x} \quad (22)$$

where the waveform is of the form $\sin(x) / x$, and $x = \text{PI} * B / \text{freq.}$

2. Angular Accuracy

The measurement of angular position is the measurement of the angle of arrival of the equiphase wavefront of the echo signal. The theoretical error of the angle measurement ($\delta\theta$) may be derived in a manner similar to the derivations of time error (range). For simplicity, the angular error in one coordinate plane only will be considered. The analysis will be extended to include angular errors in both planes. In terms of the half-power beamwidth

$$\delta\theta = \frac{0.628 * \theta}{(2 * S/N) * 0.5} \quad (23)$$

where θ is the half-power beamwidth in radians, and the units of $\delta\theta$ are the same as those of θ . [Ref.1]

3. Radar Errors Distribution

When a radar system tracks an aircraft, the target coordinates measured by the radar, such as range and angle will typically fluctuate about the true value. This error can be represented by a normal distribution $N(m, \sigma^2)$, where m is the mean or bias, and σ^2 is the variance. [Ref. 6]

Thus, given $X = N(0, 1)$, we can obtain $X' = N(m, \sigma^2)$ by setting

$$X' = m + (\sigma * X) \quad (24)$$

The C-language library can be used to generate the random number and the polar method in Reference 7, to generated standard random variables $N(0,1)$

1. Generate $U1$ and $U2$ as $U(0,1)$, using the function `drand48()`,
let $V1 = 2U1 - 1.0$ and $V2 = 2U2 - 1.0$, then

$$W = V1^2 + V2^2$$

2. If $W > 1.0$, go back to step 1. Otherwise, let

$$Y = [(-2 \ln W) / W]^{0.5}$$

$X1 = V1 * Y$, and $X2 = V2 * Y$. Then $X1$ and $X2$ are $N(0,1)$ random variables. [Ref. 7]

IV. SUMMARY

From the standpoint of a clear exposition, it is rather unfortunate that a true understanding of the radar detection problem is wrapped in complexities of statistical theory which do not convey to the practicing designer a real feel for the problem. I have attempted to alleviate this problem by confining some of the more detailed mathematical derivations to simple assumptions that limit the validity of the results.

The chief advantage of ISEAS is replication. Within a reasonable amount of time, a game can be replicated sufficiently often to obtain a detection which gives an indication of how bad the situation might be, how good it might be, and what action could be taken. Then, one or more parameters can be varied, another series played, and new results obtained. A comparison of the ranges reveals the effects of the parameter variation or variations.

In conclusion, the effectiveness of the model depends on its ability to be sensitive to changes. A very sophisticated model may take into account many elements of the encounter but in so doing may require a large amount of input data, and excessive computer run times. In addition, the increased amount of detail in the radar model may not yield a significant increase in sensitivity or increase the validity of the complete simulation.

APPENDIX A

THE RADAR OF ISEAS

```
/******
    LTjg CLAUDIO MONTERO
******/

#include "stdio.h"

#include "math.h"

#include <rad_head.h>

float  TR, RANGE, ELV, BEAR ;

int DET;

/******

    External variables to pass to the calling routines

    RANGE = Range from the radar to the target,

    ELV = Angle of elevation of the radar,

    BEAR = Bearing of the radar (relative to the ship heading)
*****/

    /* Default values for the radar */

float PRF=1000.0, AA=30, T=2e-6, RT=0.5e-6, EA=0.8, FF=9.0e9,
    PL=2.0, BL=3.0, BW=5.0e6, ST=290.0, NF=5.0,
    POWER=3.0e5, AZR=120.0, BAZ=1.5, BEL=10.0, FAN=1.0e10,
    NS=3, PJ=0.1, GJJ= 0.0, JR=45.0;

    /* Default values for the target */

float RCS=6.0, x_t=70000, y_t=20000, z_t=10000;
```

```

/*****
INPUT DATA DEFINITION:

PRF = Pulse repetition frequency, AA = Antenna altitude
T = Pulse width, RT = Recovery time, EA = Effective area
FF = Frequency, PL = Plumbing loss, BL = Beam loss
BW = Receiver bandwidth, ST = System temperature
NF = Noise figure, POWER = Transmitter power,
RCS = Target RCS, AZR= Antenna scan rate,
BAZ= Azimuth beam width, BEL= Elevation beam width
FAN= False alarm number, NS = Number of scans,
PJ = Jammer power, GJJ = Jammer antenna gain,
JR= Range from jammer to radar, x_t= X-position of target,
y_t= Y-position of target, z_t= Z-position of target (meters)
*****/

main()
{
float r_un_range(), radar_horiz(), r_min_rang(), r_cprob(),
    t_range();
    t_range(x_t,y_t,z_t);
    DET = r_un_range(PRF);
    DET += radar_horiz(AA,z_t);
    DET += r_min_range(T,RT);
    DET += r_cprob(NS);
    pass_value(x_t, y_t, z_t);
}

```

```

/*****

    Use to calculate the true range to the target in nautical miles

    given the true target position in polar coordinates

*****/

float t_range (x_target, y_target, z_target)

float x_target, y_target, z_target;

{

    float TR1,TR2;

    TR1 = pow(x_target,2.0) + pow(y_target,2.0) + pow(z_target,2.0);

    TR2 = pow(TR1,0.5);

    TR = TR2/ 1609.0;      /* From meters to N.M */

    return(TR);

}

/*****

    Use to calculate the radar unambiguous range of the target

    and return a value depending if the target is into the

    unambiguous range or not.

*****/

float r_un_range( r_prf )

float r_prf ;

{

    float RU1,RU ;

    RU1 = C_SPEED/(2.0 * r_prf);/* C_SPEED is defined in rad_head.h */

    RU = RU1 / 1609.0 ;      /* Meter to Nautical Miles */

    if ( RU >= TR )

        return (DETECTED) ;

    else

        return (UNDETECTED) ;

}

```

```

/*****

Function used to calculate the horizon of radar in N.M
depending on the altitude of the antenna and the target,
then return a value depending if the altitude of the target
allows the radar to detect it or not.

*****/

float radar_horiz ( r_ant, t_alt )
float r_ant, t_alt;
{
    float RH, theta, alpha;

    RH = 1.23 * (sqrt(r_ant));    /* RH is in N.M */
    theta = r_ant / (RH * 5280.0); /* Mile to feet * 5280 */
    alpha = t_alt / (TR * 5280.0);

/*****
tetha and alpha will be proportional to the angle of sight
of the antenna or target respectively.
*****/

    if (alpha > theta )
        return ( DETECTED );
    else
        return ( UNDETECTED );
}

```

```

/*****

Use to calculate the minimum range for detection, also return
a value depending if the range is in or out of the minimum
range zone.

*****/

float r_min_rang ( r_tau, r_taur )
float r_tau, r_taur ;    /* r_tau  = Pulse width */
(
    /* r_taur = Receiver recovery time */
    float MR1,MR;
    MR1 = (C_SPEED * (r_tau + r_taur)) / 2.0 ;
    MR  = MR1 / 1609.0;    /* Meters to Nautical Miles */
    if ( TR >= MR )
        return (DETECTED);
    else
        return (UNDETECTED);
}

/*****

Antenna gain ( r_gain ) should be used in the radar equation
since it includes the losses introduced by the antenna.

Assuming antenna efficiency is unity , Ae = A.

    Ae = effective area
    A  = actual antenna area

    r_gain = 4 * PI * Ae / SQUARE (Lamd)

*****/

```

```

float r_gain ( r_area, r_freq )

float r_area, r_freq;

{

    float lamda, AG ;

    lamda = C_SPEED / r_freq ;    /* given in meters */

    AG = (4.0 * PI * r_area ) / pow(lamda,2.0) ;

    return ( AG );

}


/*****

The system loss is the sum of all the losses. They will be
given in Db, but the losses should be in decimals to be used
in the range equation.

Plumbing loss      r_plumb

Beam shape loss    r_beam

*****/

float r_losses ( r_plumb, r_beam )

float r_plumb, r_beam;

{

    float RL1, RL2, RL;           /* RL1 will be the losses in Db */

    RL1 = r_plumb + r_beam;

    RL2 = RL1 / 10 ;

    RL  = pow(10.0,RL2) ; /* Range equation works with decimal */

    return (RL);

}

```

```

/*****
The reduction in radar signal power when propagating over a
distance R and back (two-way path) may be expressed as

$$10^{-(\alpha * R/5)}$$

, where  $\alpha$  is the attenuation coefficient
*****/

```

```

float r_attenuat( r_freq)
float r_freq;
{
    float F1, ATT1, ATT2, ATT;
    F1 = r_freq / 1.0e9;
    ATT1 = (0.000393 * F1) + 0.003001;
    ATT2 = -(ATT1 * TR / 5.0);
    ATT = pow(10.0,ATT2);
    return(ATT);
}

```

```

float j_attenuat(j_range, r_freq)
float j_range, r_freq;
{
    float F1, AJT1, AJT2, AJT;
    F1 = r_freq / 1.0e9;
    AJT1 = (0.000393 * F1) + 0.003001;
    AJT2 = -(AJT1 * j_range / 10.0);
    AJT = pow(10.0,AJT2);
    return (AJT);
}

```

```

/*****

The receiver noise generated by the thermal motion of the
conduction electrons at the receiver, are given by


$$n_{rec} = K * TS * Br * Fn$$


where K is Boltzman's constant ( 1.38e-23 joules/degree )

TS is System temperature ( 290 K )

Br is Receiver noise bandwidth (hertz)

Fn is Receiver noise figure ( equal to 5 )

*****/

float n_rec ( r_bandwid, r_temp, r_figure )
float r_bandwid, r_temp, r_figure ;
{
    float RN;
    RN =( K_BOLTZ * r_temp * r_bandwid * r_figure);
    return (RN ) ;
}

/*****

Use to calculate the number of pulses per scan (n), that
will be used in the equation to calculate the single scan
probability. ( see pag 26 for reference )

*****/

```

```

float r_pulses ( r_prf, r_azr, r_baz, r_bel )

float r_prf, r_azr, r_baz, r_bel;

{
    float r_st, r_ba, r_sfov, NP;

    r_st = 360.0 / r_azr;

    r_ba = r_baz * r_bel ;

    r_sfov = 360.0 * r_bel ;

    NP = ( r_st * r_prf * r_ba ) / r_sfov ;

    return (NP);
}
/*****

    Radar-target range (Ro) is the characteristic of a given

    radar system against a target of specified radar cross section
*****/
float r_tar_range (r_power, r_freq, t_rcs)

float r_power, r_freq, t_rcs;

{
    float RT1, RT2, lamda, AG, RL, RN, ATT, RTR;

    float r_gain(), r_losses(), n_rec(), r_attenuat();

    lamda = C_SPEED / r_freq;

    AG = r_gain(EA,FF);

    RL = r_losses(PL,BL);

    RN = n_rec(BW,ST,NF);

    ATT = r_attenuat(FF);

    RT1 = (r_power * (pow(AG,2.0)) * (pow(lamda,2.0)) * t_rcs * ATT);

    RT2 = pow((4*PI),3.0) * RL * RN ;

    RTR = (pow((RT1/RT2),0.25))/1609.0;

    return (RTR);
}

```

```

/*****

The reference jamming range that will be use to get the

single scan probability in the presence of jamming.

*****/

float jam_range(j_power, g_jammer, r_freq, r_bandwid)

float j_power, g_jammer, r_freq, r_bandwid;

{

    float lamda, GJ, RJ1, RJ2, AG, RL, RN, AJT, RJ ;

    float r_gain(), r_losses(), n_rec(), j_attenuat();

    AG = r_gain(EA,FF);

    RL = r_losses(PL, BL);

    RN = n_rec(BW,ST,NF);

    AJT = j_attenuat(JR,FF);

    lamda = C_SPEED / r_freq;

    GJ = pow(10.0,(g_jammer/10.0)); /* change Db to decimal */

    RJ1 = ((j_power/1.0e9) * AG * GJ * pow(lamda,2.0) * r_bandwid * AJT);

    RJ2 = pow((4*PI),2.0) * RN * (RL/2.0) ;

    RJ = pow((RJ1/RJ2),0.5)/1609.0;

    return (RJ);

}

```

```

/*****

```

The signal to noise ratio in the receiver

```

*****/

```

```

float r_sig_noise( j_range)

float j_range;

{

    float RSN1, RSN2, RTR, RJ, RSN;

    float r_tar_range(), jam_range();

    RTR = r_tar_range(POWER,FF,RCS);

    RJ = jam_range(PJ,GJJ,FF,BW);

    RSN1 = pow((RTR/TR),4.0);

    RSN2 = 1 +(pow((RJ/j_range),2.0));

    RSN = (RSN1/RSN2);

    return(RSN);

}

```

```

/*****

```

K is a factor of the radar equation which is a function of
n (pulses per scan) and m (false alarm number), where

$$K_{db} = 10 \log K$$

$$K_{db} = -6 \log n + .4 \log m + 7.2$$

$$K_{factor} = 10^{.1(K_{db})}$$

(see example page 34 for reference)

```

*****/

```

```

float k_factor ( r_false )

float r_false ;

{

    float k_db1, NP, KF ;

    float r_pulses();

    NP = r_pulses(PRF,AZR,BAZ,BEL);

    k_db1 = ((-6.0 * log10(NP)) + (0.4 * log10(r_false))

            + 7.2 ) * 0.1;

    KF = pow(10.0,k_db1);

    return (KF);

}

/*****

    Single scan probability of detection at range R, is given as

    PSS = exp [ -k /(S/N)]

    ( see example page 34 for reference )

*****/

float r_sprob ()

{

    float PSS1, KF, RSN, PSS;

    float k_factor(), r_sig_noise();

    KF = k_factor(FAN);

    RSN = r_sig_noise(JR);

    PSS1 = -( KF / RSN );

    PSS = exp (PSS1);

    return (PSS);

}

```

```
/******
```

The probability that the target has been detected after "s"

scans, if we consider PSS constant, is given by

$$\frac{s}{P} = 1 - (1 - PSS)^s$$

(see page 35 for reference)

then returns a value depending if the cumulative probability

is larger than 90 % of detected probability or not.

```
*****/
```

```
float r_cprob ( r_scan )
```

```
float r_scan;
```

```
{
```

```
    float PC1, PC2, PC, PSS ;
```

```
    float r_sprob();
```

```
    PSS = r_sprob();
```

```
    PC1 = (1 - PSS);
```

```
    PC2 = pow(PC1, r_scan);
```

```
    PC = (1 - PC2);
```

```
    if (PC >= 0.90)
```

```
        return (DETECTED);
```

```
    else
```

```
        return (UNDETECTED);
```

```
}
```

```

/*****

This function will calculate range, elevation and bearing
if the target is detected by the radar, including the range
and angular error.

*****/
pass_value(x_target, y_target, z_target)

float x_target, y_target, z_target;

{

    float x_r, y_r, z_r, range1, range2, ran_error,
        elv_error, bear_error;

    float r_rang_error(), r_elv_error(), r_bear_error();

    if (DET == 4.0)
    {

        x_r = x_target;

        y_r = y_target;

        z_r = z_target;

        range1 = pow(x_r,2.0) + pow(y_r,2.0) + pow(z_r,2.0);

        range2 = pow(range1,0.5) ;

        ran_error = r_rang_error(BW,T);

        elv_error = r_elv_error(BEL);

        bear_error = r_bear_error(BAZ);

        RANGE = (range2 + ran_error) / 1609.0 ;

        ELV = ((asin(z_r/range2)) * 180.0/PI) + elv_error ;

        BEAR = ((atan2(x_r,y_r)) * 180.0/PI) + bear_error ;

    }

    printf("\nRange is = %.2f N.M",RANGE);

    printf("\nElevation is = %.2f Deg",ELV);

    printf("\nBearing is = %.2f Deg",BEAR);

}

```

```

/*****

    This function will calculate the range and angular error
    as in the formula on page 38.

*****/

float r_rang_error (r_bandwid, r_tau)

float r_bandwid, r_tau;

{

    float RE1, RE2, RER, RSN, RAX;

    float random(), r_sig_noise();

    if (DET == 4)

        {

            RAX = random();

            RSN = r_sig_noise(JR);

            RE1 = r_tau / (4.0 * r_bandwid * RSN);

            RE2 = pow(RE1,0.5);

            RER = RAX * RE2 * C_SPEED / 2.0;

            return(RER);

        }

}

```

```

float r_elv_error ( r_bel )

float r_bel;

{

    float RAX, ELER, RSN;

    float random(), r_sig_noise();

    if (DET == 4)

        {

            RAX = random();

            RSN = r_sig_noise(JR);

            ELER = RAX * 0.628 * r_bel / (2.0 * pow((2.0 * RSN),0.5));

            return(ELER);

        }

}

float r_bear_error (r_baz)

float r_baz;

{

    float RAX, AZER, RSN;

    float random(), r_sig_noise();

    if (DET == 4)

        {

            RAX = random();

            RSN = r_sig_noise(JR);

            AZER = RAX * 0.628 * r_baz / (2.0 * pow((2.0 * RSN),0.5));

            return(AZER);

        }

}

```

```

/*****

Creates a random variable number  $N(0,1)$ , using the C-language
library.

*****/

```

```

float random()
{
    double x, y, z, v1, v2, w=2.0 ;
    float RAX;
    while ( w > 1.0 )
    {
        x = drand48();
        y = drand48();
        v1 = (2 * x) - 1.0;
        v2 = (2 * y) - 1.0;
        w = pow(v1,2.0) + pow(v2,2.0);
    }
    z = ((-2.0) * log(w)) / w;
    RAX = (pow(z,0.5)) * v1;
    return(RAX);
}

```

APPENDIX B

TRACKING RADAR OF ISEAS

```

/*****
    LTJG CLAUDIO MONTERO
*****/

#include "stdio.h"

#include "math.h"

#include <rad_head.h>

float TR,TR_RANGE,T_ELV,T_BEAR;

int TRACK;

/*****

EXTERNAL VARIABLES

    TR_RANGE = Range to the target,   T_ELV = Angle of elevation,
    T_BEAR = Bearing relative to the ship head.

*****/

    /* Default values for the tracking radar */

float AAT= 40.0, EAT=0.6, BWT=4.0e4, CST=4.0, POWT=1.2e5,
      FFT=2.0e9, GLT=1.5, BLT=0.5, ST=290, NF=5.0, TAZ=1.0,
      TBEL=1.5;

    /* Default values for the target */

float RCS=1.0, x_t=30000, y_t=20000, z_t=400;

/*****
INPUT DATA DEFINITION

AAT = Antenna altitude (feet), EAT = Effective area antenna
BWT = Receiver bandwidth, CST = Critical S/N ratio,
POWT = Transmitter power, FFT = Frequency tracking radar
GLT = Track gate losses, BLT = Beam losses

TAZ = Azimuth beam width(tracker), TBEL = Elevation beam width
*****/

```

```

main()
{
    float t_range(), track_horiz(), track_horiz();

    t_range(x_t,y_t,z_t);

    TRACK = track_horiz(AAT,z_t);

    TRACK += check_tracking();

    pass_track(x_t,y_t,z_t);
}

/*****

    Use to calculate the range to the target in N.M

*****/

float t_range (x_target, y_target, z_target)
float x_target, y_target, z_target;
{
    float TR1,TR2;

    TR1 = pow(x_target,2.0) + pow(y_target,2.0) + pow(z_target,2.0);

    TR2 = pow(TR1,0.5);

    TR = TR2 / 1609.0;

    return(TR);
}

```

```

/*****

Function used to calculate the horizon of the radar in nautical
miles depending on the altitude of the antenna and altitude of
the target. Then returns a value depending on if the radar
can detect the target or not.

*****/
float track_horiz( tr_ant, z_target )

float tr_ant, z_target;

{

    float TH, theta, alpha;

    TH = 1.23 * (sqrt(tr_ant));

    theta = tr_ant / (TH * 5280.0);

    alpha = z_target / (TR * 5280.0);

    if (alpha > theta )

        return ( DETECTED );

    else

        return ( UNDETECTED );

}

/*****

Antenna gain will be used in the radar maximum range equation

*****/
float tr_gain( tr_area, tr_freq)

float tr_area, tr_freq;

{

    float lamda, AGT;

    lamda = C_SPEED / tr_freq ;

    AGT = (4.0 * PI * tr_area) / pow (lamda,2.0);

    return(AGT);

}

```

```

/*****

    System losses

    Track gate losses      tr_gate

    Beam shape loss       tr_beam

*****/

float tr_losses(tr_gate, tr_beam)

float tr_gate, tr_beam;

{

    float TRL1, TRL;

    TRL1 = (tr_gate + tr_beam) / 10.0;

    TRL = pow(10.0, TRL1);

    return(TRL);

}

/*****

    Atmospheric attenuation

*****/

float tr_attenuat(tr_freq)

float tr_freq;

{

    float F1, ATTR1, ATTR2, ATTR ;

    F1 = tr_freq / 1.0e9;

    ATTR1 = (0.000393 * F1) + 0.003001;

    ATTR2 = -(ATTR1 * TR / 5.0);

    ATTR = pow(10.0, ATTR2);

    return(ATTR);

}

```

```

/*****

The receiver noise

*****/
float noise_rec( tr_bandwid, r_temp, r_figure)

float tr_bandwid, r_temp, r_figure;

{

    float TRN;

    TRN = (K_BOLTZ * r_temp * tr_bandwid * r_figure);

    return(TRN);

}

/*****

Target reference range (Ro) , taking the radar cross section
equal to one.

*****/
float tr_ref_range(tr_power,tr_freq)

float tr_power, tr_freq;

{

    float lamda, AGT, TRL, TRN, ATTR, TRR1, TRR2, TRR;

    float tr_gain(), tr_losses(), noise_rec(), tr_attenuat();

    lamda = C_SPEED / tr_freq;

    AGT = tr_gain(EAT,FFT);

    TRL = tr_losses(GLT,BLT);

    TRN = noise_rec(BWT,ST,NF);

    ATTR = tr_attenuat(FFT);

    TRR1 = (tr_power * pow(AGT,2.0)) * pow(lamda,2.0) * 1.0 * ATTR;

    TRR2 = pow((4*PI),3.0) * TRL * TRN;

    TRR = (pow((TRR1 / TRR2),0.25)) / 1609.0;

    return(TRR);

}

```

```

/*****

The maximun range

*****/

float tr_max_range( t_rcs )

float t_rcs;

{
    float TRM, TRR;

    float tr_ref_range();

    TRR = tr_ref_range(POWT,FFT);

    TRM = TRR * pow(t_rcs,0.25);

    return(TRM);

}

check_tracking()

{

    float TRM;

    float tr_max_range();

    TRM = tr_max_range(RCS);

    if ((0.9 * TRM) >= TR)

        return(DETECTED);

    else

        return(UNDETECTED);

}

```

```

/*****

    Calculate the signal to noise ratio

*****/
float tr_sig_noise()
{
    float TRM, TSN;

    float tr_max_range();

    TRM = tr_max_range(RCS);

    TSN = pow((TRM / TR),4.0);

    return(TSN);
}
/*****

    Create a random variable number  $N(0,1)$ , using the C-language
    library.

*****/
float random()
{
    double x, y, z, v1, v2, w=2.0;

    float RAN;

    while ( w > 1.0 )
    {
        x = drand48();

        y = drand48();

        v1 = (2 * x) - 1.0;

        v2 = (2 * y) - 1.0;

        w = pow(v1,2.0) + pow(v2,2.0);

    }

    z = ((-2.0) * log(w)) / w;

    RAN = (pow(z,0.5)) * v1;

    return(RAN);
}

```

```

/*****
This function will calculate range, elevation and bearing;

if the target is detected by the radar

*****/
pass_track(x_target, y_target, z_target)

float x_target, y_target, z_target;

{
    float x_r, y_r, z_r, range1, range2, ran_error, elv_error,
        bear_error;

    float tr_rang_error(), tr_elv_error(), tr_bear_error();

    if (TRACK == 2.0)
    {
        x_r = x_target;
        y_r = y_target;
        z_r = z_target;

        range1 = pow(x_r,2.0) + pow(y_r,2.0) + pow(z_r,2.0);
        range2 = pow(range1,0.5);

        ran_error = tr_rang_error(BWT,FFT);
        elv_error = tr_elv_error(TBEL);
        bear_error = tr_bear_error(TAZ);

        TR_RANGE = (range2 + ran_error) / 1609.0;

        T_ELV = ((asin(z_r/range2)) * 180.0/PI) + elv_error ;
        T_BEAR = ((atan2(x_r,y_r)) * 180.0/PI) + bear_error ;
    }

    printf("\nRange is = %.2f N.M",TR_RANGE);
    printf("\nElevation is = %.2f Deg",T_ELV);
    printf("\nBearing is = %.2f Deg",T_BEAR);
}

```

```

/*****

This function will calculate the range and angular error
as in the formula in page 38.

*****/

float tr_rang_error( tr_bandwid, tr_freq )
float tr_bandwid, tr_freq;
{
    float x, RAN, TER1, TER2, TER, TSN;
    float random(), tr_sig_noise();
    if ( TRACK ==2 )
    {
        RAN = random();
        TSN = tr_sig_noise();
        x = PI * tr_bandwid / tr_freq;
        TER1 = PI * tr_bandwid * pow((2.0*TSN),0.5);
        TER2 = sin(x*PI/180) / x;
        TER = RAN * 1.73205 * TER2 * C_SPEED / (TER1 * 2.0);
        return(TER);
    }
}

```

```

float tr_elv_error( tr_bel )

float tr_bel;

{
    float RAN, TELE, TSN;

    float random(), tr_sig_noise();

    if ( TRACK == 2 )
    {
        RAN = random();

        TSN = tr_sig_noise();

        TELE = (RAN * 0.628 * tr_bel) / (2.0 * pow((2.0*TSN),0.5));

        return(TELE);
    }
}

float tr_bear_error( tr_bear )

float tr_bear;

{
    float RAN, TBEA, TSN;

    float random(), tr_sig_noise();

    if ( TRACK == 2 )
    {
        RAN = random();

        TSN = tr_sig_noise();

        TBEA = (RAN * 0.628 * tr_bear) / (2.0 * pow((2.0 * TSN),0.5));

        return(TBEA);
    }
}

```

```

/*****

rad_head.h

Define the parameter to be used in the search radar and
tracking radar programs.

*****/

#define C_SPEED 3.0e8      /* meter/sec      */
#define K_BOLTZ 1.38e-23  /* joules/degree */
#define TRUE    1
#define FALSE   0
#define DETECTED 1
#define UNDETECTED 0

```

APPENDIX C

USERS' GUIDE

This appendix provides users' instructions for the radar detection model.

DATA function is used to read the input parameters in the computer. The function has two beneficial features. It assigns the initial values to the parameters, and it allows the player to change the values at the beginning of the program. All values used in the first case of a job are continued into the second case, except those specifically changed.

Table 1 shows the input parameters to consider.

TABLE 1
RADAR DETECTION MODEL INPUTS

<u>INPUT</u>	<u>DEFINITION</u>
r_power	Average transmitter power (Watts)
r_temp	Receiver noise temperature (290 K)
r_prf	Pulse repetition frequency (Pulses)
r_tau	Pulse width (sec)
r_taur	Receiver recovery time (sec)
r_ant	Antenna height (feet)
r_area	Antenna area (Square meters)
r_freq	Radar frequency (hertz)
r_bandwid	Radar receiver bandwidth (hertz)

INPUTDEFINITION

r_figure	Receiver noise figure
c_signal	Critical signal to noise ratio
r_false	False alarm number (1.e6 to 1.e12)
r_scan	Number of scans
r_azr	Antenna scan rate (deg/sec)
r_baz	Antenna azimuth beam width (deg)
r_bel	Antenna elevation beam width (deg)
r_plum	Plumbing loss (Db)
r_beam	Beam shape loss (Db)
j_power	Jammer power (Watts /GHz)
g_jammer	Jammer antenna gain (Db)
j_range	Range from jammer to the radar (N.M)
tr_power	Tracking radar transmitter power(Watts)
tr_ant	Antenna height(feet)
tr_area	Antenna area(Sq.meters)
tr_freq	Tracking radar frequency(hertz)
tr_bandwid	Tracking radar bandwidth (hertz)
tr_signal	Critical signal to noise ratio
tr_gate	Track gate losses (Db)
tr_beam	Beam shape losses (Db)
tr_bel	Antenna elevation beam width (deg)
tr_bear	Antenna azimuth beam width (deg)

GIVEN BY THE TARGET

INPUT

DEFINITION

t_rcs	Target radar cross section (Sq.meters)
x_t	X-position of the target(Meters)
y_t	Y-position of the target(Meters)
z_t	Z-position of the target(Meters)

APPENDIX D

SAMPLE INPUT VALUES

To provide an illustration of the use of the computer model, let us suppose that the radar system possesses the following parameter values

<u>INPUT</u>	<u>VALUES</u>	
r_power	2.0e5	Watt
r_temp	290	K
r_prf	1500	Pulses/sec
r_tau	2.0e-6	sec
r_taur	0.5e-6	sec
r_ant	30.0	feet
r_area	0.8	Square Meters
r_freq	9.0e9	Hz
r_bandwid	5.0e6	Hz
r_figure	5.0	
c_signal	5.0	
r_false	1.0e10	
r_scan	3.0	Scans
r_azr	120	deg/sec
r_baz	1.5	deg
r_bel	10.0	deg
r_plum	2.0	Db
r_beam	3.0	Db
j_power	10 to 0.1	Watts/GHz

<u>INPUT</u>	<u>VALUE</u>	
g_jammer	1.0	Db
j_range	60.0	N.M
tr_power	1.2e5	Watts
tr_freq	4.0e9	Hz
tr_ant	30.0	feet
tr_area	0.6	Sq.meters
tr_bandwid	4.0e4	Hz
tr_signal	5.0	
tr_gate	1.0 to 1.6	Db
tr_beam	0.5	Db
tr_bear	1.1	Deg
tr_bel	0.7	Deg

GIVEN BY THE TARGET

t_rcs	5.0	Sq.meters
x_t	40000	Meters
y_t	35000	Meters
z_t	5000	Meters

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